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Commissioning a laser metrology truss for active optics on the Large Binocular Telescope

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ABSTRACT

LBTO, in partnership with GMTO, has been developing a laser-truss-based metrology system for the active alignment of telescope main optical components. Positive initial results convinced LBTO to commence to develop a "pathfinder" integrated operational active-optics system at prime focus, utilizing this technological approach. The prime-focus active-optics system benefits LBTO directly in improved system performance and is also very useful for GMTO in developing and gaining experience with a critical technical component of the GMT Telescope Metrology System. This paper describes the current system, which is now commissioned and operates in support of regular scientific observing. Technical aspects unique to direct laser truss metrology, such as system stability, the effects of correlated and uncorrelated noise, and the benefits of channel redundancy, will be discussed. Commissioning results and general system performance will also be reported. The paper will conclude with a section discussing some of the unexpected insights and improvements that the TMS has brought about at LBT by enabling the measurement of "clean" aberration data for aberrations arising from shape change on the borosilicate primary mirrors.

Keywords: LBT, Optical Alignment, Telescope Alignment, Laser Tracker, 3-D Metrology

1. INTRODUCTION

Since 2017 LBTO, in partnership with GMTO, has been developing a 3-D direct metrology (laser-truss) based system for the active alignment of telescope main optical components to each other and to instruments[1,2]. The effort has addressed needs of both organizations; LBTO with the opportunity to assess the performance of a new technological approach to telescope alignment, and the GMTO with the opportunity to prototype and field-test a system that has been identified as a crucial "missing link" in the active-optics chain between open-loop modelling and wavefront-sensing for ELT-scale telescopes.

Following two years of investigation, the positive results obtained convinced LBTO to commence the development of an integrated operational active-optics system at prime-focus, based on this technological approach. A team drawn from LBTO, Steward Observatory, GMTO, the Wyant College of Optical Sciences and Mersenne Optical Consulting was formed to complete the development of this Telescope Metrology System (TMS). A full technical description of the system including initial results of "passive mode" observing were last reported by this team in 2020[3,4]. At the time of publication of Ref 4. in late 2020, a list of "key performance attributes" were proposed as driving high-level requirements for the system development. These were:

- **Reliability.** An agreed set of standards for reliability of operations.

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- **Error Handling** (actually, part of reliability). The system must, at worst, not degrade the current alignment performance achieved by the LBC. In cases where it is not able to operate, a "seamless exit" must be demonstrated.
- **Accuracy.** The system must demonstrate volumetric measurement accuracies in operating conditions of the order of 5 microns radial.
- **Operability.** The system must not significantly complicate, or otherwise add to the workload, of the telescope operators.

Starting in early 2022, a "binocular laser truss" Telescope Metrology System has been employed to actively control optics positions during prime focus operations. Following an iterative development process, the system went into regular use during Prime Focus science operations in Q2 2022.

This paper will describe the system that has been developed to meet the listed performance benchmarks. Section 2 of this paper will give a system overview. Section 3 will discuss hardware. Section 4 will expand on the inverse kinematics descriptions given in Refs 1-4 with some discussion of redundant systems and system noise. Section 5 will describe the currently deployed software and interfaces with the Telescope Control System (TCS). Section 6 will summarize on-sky results to date, and Section 7 concludes with a description of how TMS has led to improved thermal modelling for mirror segment shape.

2. SYSTEM OVERVIEW

The LBT supports several different optical configurations, including the binocular prime focus mode, with the Large Binocular Cameras, or "LBCs", Folded or Direct Binocular Gregorian modes, supporting LUCI, MODS and PEPSI instruments, and an interferometric mode, combining beams from the two 8.4 m Nasmyth Gregorian foci in the LBTI instrument. The TMS is currently deployed to support alignment of the LBC configuration.

The LBCs are fast imaging cameras (working at ~ f/1.4). The LBC's are not supported operationally by a closed loop active optics system. Rather, open loop models are used to correct for optics deflections caused by structural temperature changes and elevation changes. When collimation is required, the system is defocused and image analysis of defocused stars on the science detectors is conducted to determine both deformations of the primary mirrors and misalignments of the system optics, enabling correction.

When the temperature is stable, and for observations in which the elevation does not change significantly, the system can maintain satisfactory image quality over useful observing periods, but in less stable thermal states, or when significant elevation changes are required, collimation must be run to completion before observing can begin. This produces observing overheads of at least several minutes, and sometimes significantly longer, per collimation run.

The Telescope Metrology System, or TMS is a laser-truss system and has been thoroughly described in References (1) - (4). In this paper it will be assumed that interested readers will have access to this information. This paper will be focused primarily on developments since late 2020, to avoid repetition. The TMS, is capable of measuring the relative position and orientation of the LBT primary mirrors with respect to the LBC correctors, with absolute accuracies of the order of a few microns, and with update rates of less than 20 seconds. Considering the lack of closed-loop active optics on LBC, the motivation to develop the TMS for LBC is clear. By controlling the relative position of the optical components, the only remaining significant "uncontrolled" factor affecting image quality is thermal shape change of the primary mirrors. This aspect of LBC TMS will be discussed in Section 7.

3. HARDWARE

A brief summary of the system hardware is given here, and further detail can be found in Refs 3 and 4. The Telescope Metrology System, or "TMS", is comprised of a network of absolute distance measuring laser interferometers. A single commercially-available interferometer system manufactured by Etalon, a Hexagon company, produces 28 "independent" channels of fiber interferometer. Fibers are run from the base unit in the Auxiliary Control Room up to the telescope (via a fiber drape between the observatory building and the telescope at the elevation axis).

Fibers terminate at collimators, that are attached directly to the LBT primary mirror sides. Each collimator is aligned to direct its beam to one of six retroreflector targets, three on each of the two LBC prime focus units. Figure 3-1 illustrates the basic disposition of length measurement channels connecting a primary mirror to a prime focus corrector. A "map" of the current configuration is given in Figure 3-2.

A laser tracker is used to survey the position of the collimators and corresponding retroreflector targets. Once this is done the Inverse Kinematics matrices can be set up as described in the references and in Section 4 below.

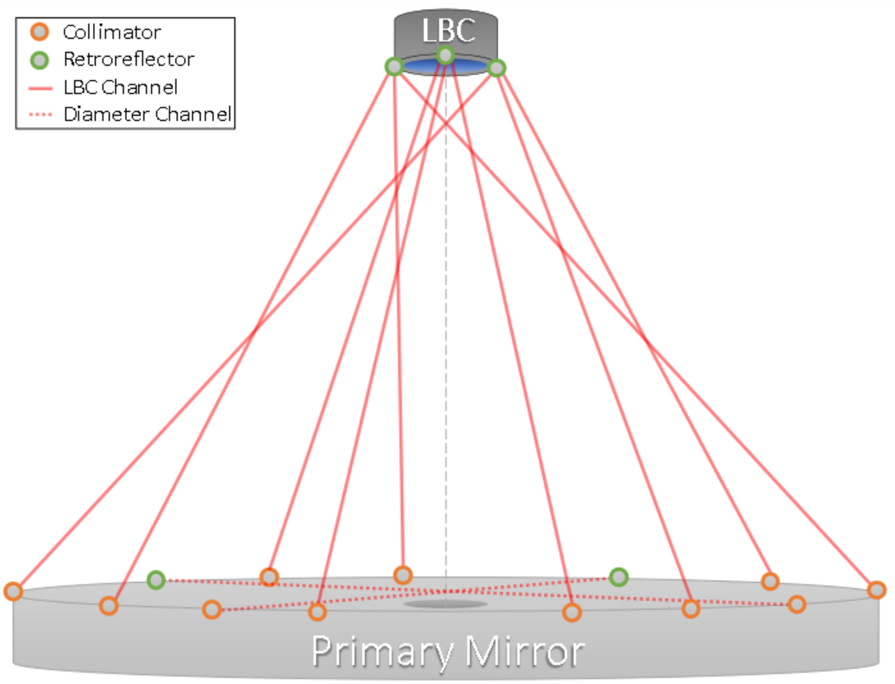

Figure 3-1 Cartoon representation of a laser truss for one primary mirror- prime focus corrector pair. Accuracy is optimized by maximizing the angle between beams at each retroreflector.

(8/27)	Channel	Align to
	Dx	
1	1	Y+
2	2	Diameter-10
-	3	
4	4	Y+
5	5	X+
6	6	X-
7	7	
-	8	
-	9	
10	10	Y+
11	11	X+
12	12	X-
13	13	X+
-	14	
15	15	Y+
-	16	
	Sx	
17	17	Y+
18	18	Y+
29 (OVFLW)	19	Diameter (the rr is not installed yet)
20	20	X+
30 (OVFLW)	21	X-
22	22	X-
23	23	Y+
24	24	X+
-	25	
26	26	X-
27	27	Y+
28	28	X+

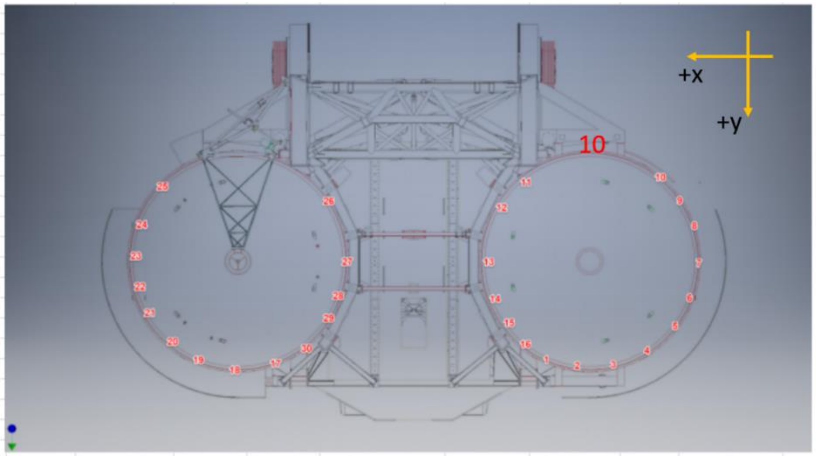

Figure 3-2. The red numbers in the figure indicate the positions of invar plates (with magnets) to which collimator mounts can be coupled. The two columns map the interferometer channel numbers to the numbered locations on the telescope. Correct "book-keeping" is critical and a systematic approach to channel numbering is recommended.

Of the four "key performance attributes" listed in the introduction, three of them: "reliability, error handling and accuracy" are achieved or improved by making a "redundant truss". A minimum of six channels is required to measure the six-degrees of translational plus rotational freedom in relative change in position and angle between each primary mirror and its corresponding LBC hub. A convenient term for describing the six-term vector giving an objects translation and rotation is the "pose" of the object.

"Real-time" construction of Inverse Kinematics matrices allows seamless handling of dropped channels, as will be described in more detail in the following section.

Two types of achromatic fiber collimator have been used, one producing a 3.5 mm beam and the other, a 7 mm beam. It is now clear that the larger beam collimator has a useful extra working range of lateral decentre of the beam w.r.t. the retroreflector vertex, an improvement of approximately 50%, and this larger collimator will be standardized for future channels.

Several channels have become inactive over the course of the last two years and indications are that broken or damaged fibers are the problem. Replacement fibers will be provided in future with multi-core single mode fibers running to patch-panel boxes mounted near the primary mirrors. From these the cores can be split to individual fibers and run to the collimators. In this way a large number of fibers, including multiple spares, can be produced with a relatively small effort in the fiber run, and good redundancy.

The only other hardware change of note since the late 2020 reports is that the idea of measuring the borosilicate primary mirror diameter to allow for focus compensation is now redundant. A new scheme, based on using data from M1 thermocouples, has proven to be a useful way of determining thermal focus from mirror shape.

Apart from the change to multi-core fibers, and standardizing on the 7 mm-beam collimators, there are two significant changes envisaged for the system. These are to improve the collimator mounts (see Figure 4-2 below), to reduce channel length noise, and to extend the metrology system to support more LBT operational modes. The impact of channel noise on measurement accuracy will be discussed in the following section.

Overall, the hardware has proven to be reliable, and maintenance of the system has not been particularly demanding, with only very occasional realignment being required on one or two channels. The interferometer has proven to be robust and suitable for high-duty-cycle telescope alignment in a working observatory environment.

4. INVERSE KINEMATICS

For readability reasons, a description of the basic inverse kinematics development used in the TMS will be given here, followed by more detail regarding noise and channel-dropping. In general, the forward kinematics for a laser truss system, mapping the changes in channel lengths to changes in pose $\Delta(\theta_x, \theta_y \theta_z, x, y, z)$ of the measured object, is impossible to calculate exactly. The inverse problem, mapping changes in pose to channel length changes is trivial. For small changes in pose, as typically occur in the misalignment of LBT optical components, the kinematics can be linearized, and the kinematic equations are reduced to the Jacobian matrix of sensitivities describing the differential changes in the channel lengths due to differential motion of the primary mirror an LBC hub. This allows us to simply invert the inverse-kinematics Jacobian matrix to obtain the sought-after forward-kinematics, mapping changes in the length of each laser gauge to changes in pose. Figure 4-1 below lays out the general geometry for the laser truss kinematics. The primary mirror is represented by the cyan disc and the LBC hub is represented by the red disc. A single channel (vector $\boldsymbol{l_i}$) connects a collimator at $\boldsymbol{b_i}$ on the primary mirror to a retroreflector at $\boldsymbol{c_i}$ on the LBC.

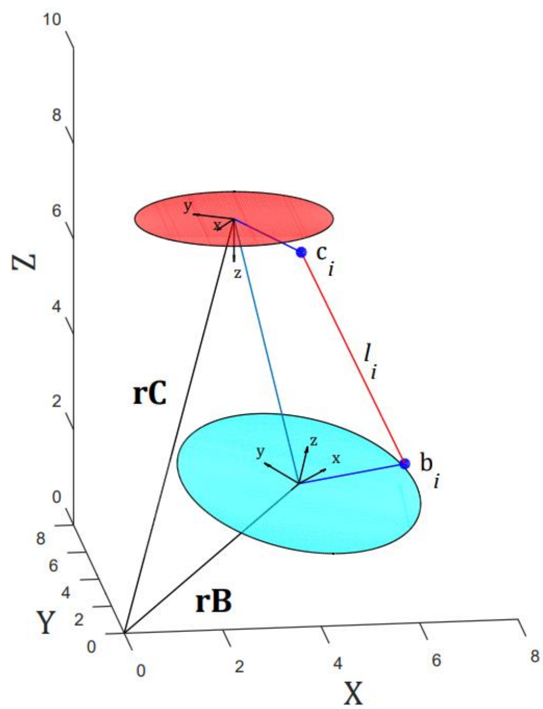

Figure 4-1 . Coordinate frames used in calculating the inverse kinematics of the TMS. The LBC hub is represented by the red disk with origin rC. The primary mirror is represented by the cyan disk with origin rB. While this is a general representation, with an arbitrary coordinate system, for convenience the coordinate system can be made to correspond to that of the primary mirror hexapod, by setting ***rB*** to zero.

For convenience, $\boldsymbol{r_B}$ can be set to 0, and the hub retroreflectors also transformed to this coordinate system, giving a coordinate system that corresponds to the primary mirror position actuator coordinate system. Then,

$$l_i = c_i - b_i \tag{1}$$

Next, unit vectors are produced from the $\boldsymbol{l_i}$:

$$\boldsymbol{e_i} = \frac{\boldsymbol{l_i}}{|\boldsymbol{l_i}|} \tag{2}$$

From these unit vectors, sensitivities of the lengths $\boldsymbol{l_i}$ to perturbations in each of the six controllable degrees of freedom of the primary mirror position can be calculated. Rotational sensitivities are given by components of the cross-product

$$E_i = c_i \times e_i, \tag{3}$$

and translational sensitivities are simply the components of $\boldsymbol{e_i}$.

The inverse kinematics equations are then given by a Jacobian sensitivity matrix, J, representing the pose-sensitivities of each channel length, multiplied into a pose-change vector, giving the resultant changes in channel length.

$$\begin{pmatrix} E_{1i} & \cdots & e_{ik} \\ \vdots & \ddots & \vdots \\ E_{ni} & \cdots & e_{nk} \end{pmatrix} \cdot \begin{pmatrix} \Delta\theta_x \\ \Delta\theta_y \\ \Delta\theta_z \\ \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} = \begin{pmatrix} \Delta l_1 \\ \vdots \\ \Delta l_n \end{pmatrix}. \tag{4}$$

The Jacobian in (4) has six columns for six degrees of freedom, and n rows for n channels. Thus, the desired forward kinematics can be found by taking product of the inverse J^{-1} and the measured channel length changes.

$$\begin{pmatrix} E_{1i} & \cdots & e_{ik} \\ \vdots & \ddots & \vdots \\ E_{ni} & \cdots & e_{nk} \end{pmatrix}^{-1} \cdot \begin{pmatrix} \Delta l_1 \\ \vdots \\ \Delta l_n \end{pmatrix} = \begin{pmatrix} \Delta\theta_x \\ \Delta\theta_y \\ \Delta\theta_z \\ \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}. \tag{5}$$

The minimum number of linearly independent channels required to obtain a pose-change vector is six. Further minimum requirements for valid channel configurations are that at least three retroreflectors receive at least one channel and that at least two retroreflectors receive at least two channels. In the case of valid channel configurations with six channels, the Jacobian in Eq. (4) is 6x6 and invertible. If one channel is missing from a given measurement dataset, then the system is underdetermined, and no pose solution can be found. Channels can be missed for a variety of reasons. Individual channels may produce noisy results if they are "at the edge of their alignment", issues may arise with collimator mounts etc. To improve system robustness, a redundant truss has been produced for each LBC hub, with one spare channel aimed at each of the three retroreflectors.

The Jacobians for the redundant truss have more than 6 rows. In this case the pseudo-inverse of the Jacobian is used to produce the forward kinematics equations. With a redundant truss, in a given measurement set the number of available channels can be first determined. A Jacobian such as in (4) is produced with the available channels and inverted as in (5) to produce the forward kinematics solutions.

In the absence of measurement noise, any valid channel configuration having six or more channels, will give identical results for pose. However, it has become clear that the presence of even small amounts of uncorrelated noise in measurement channels can lead to large differences in the delta-pose calculation for different valid combinations of available channels.

Figure 4-2. One of the 3.5 mm beam diameter collimators and its mount. The silver invar plate is bonded to the primary mirror wall. The plate contains magnets and provides a three-ball kinematic interface to the corresponding black mounting plate carrying the collimator. These collimator mounts, with a universal range of adjustment, were well suited for prototyping activities, where various geometries were being tried. A more dimensionally stable design is envisaged now as an upgrade path.

For example, modelling shows that errors in translation of several tens of microns can occur when channel-configurations are switched in the kinematics equations in the presence of uncorrelated channel length noise of the order of $\delta = 2\,microns$. Fortunately, analysis of large amounts of channel data indicates that high-frequency noise, attributable to such factors as atmospheric turbulence and opto-mechanical vibration, is typically occurring at values an order of magnitude less, typical values are 200 nm. However, over longer timescales of tens of minutes to hours, other sources of uncorrelated noise arise, and the result is that the system will produce unwanted jumps when channel configurations are changed. This noise also reduces the accuracy of the system in “blind setting” of the optics positions at the start of the night, using old reference vectors. At this stage the suspected source of this noise is the collimator mounts (see Figure 4-2). These mounts were designed to support prototyping activities and as such required full adjustment ranges for pointing. It is now intended to redesign these collimator mounts with a much smaller range of “fine adjustment” with a particular configuration in mind, with a goal to improve stability at the few-micron level. The following section will describe the currently adopted operational approaches, that are in part driven by the existence of this noise instability. It will be shown that useful collimation results are obtained.

5. SOFTWARE AND CONTROL

The current level of system instability from channel noise has led to several mitigation strategies.

- At the start of the night a previous “reference length vector” recorded immediately following an active optics collimation, is used to position the primary mirrors. The start-of-the night solutions are still quite good, typically the only significant adjustment required is focus, and that arises from thermal shape change in the borosilicate mirrors (more on this later).

- Observing starts with collimation, using geometrical analysis of defocused stars on the science detectors. Once the telescope is collimated, channel lengths are recorded and stored as a reference set. Subsequent updates of channel length measurement are then used to calculate change in pose from this reference. A reference is kept until image quality monitoring indicates that re-collimation is required.

- In the event of a dropped channel, the immediately preceding measurement that contained the same complement of channels as in the reference set is used to determine a correction term for pose calculations with the reduced set of channels. The missing channel is deleted from the Jacobian matrix used for that set of data, and this truncated Jacobian is inverted and used to calculate a new "change of pose" vector (with respect to the reference vector). The difference in this new "change of pose" vector and the one calculated with the full complement of channels is stored as an error term. This pose error is then assumed to be a "quasi-constant" and stored to be subtracted from all subsequent measurements with the same channel configuration.

While these schemes all represent some compromise, driven by the existence of noise in the system, in practice they enable a system that provides a very useful degree of control of flexural and structural-thermal misalignment. It is anticipated that efforts to drive down system noise will only improve on this.

Beyond the basic kinematics calculations and operating strategies described so far, there is considerable detail involved in the practical implementation of a laser truss as part of a closed loop active optics system working within the Telescope Control System architecture. There is so much detail that the topic deserves a paper of its own, and only a superficial description can be given here.

Figure 5-1 illustrates the sequence of steps involved in each measurement cycle.

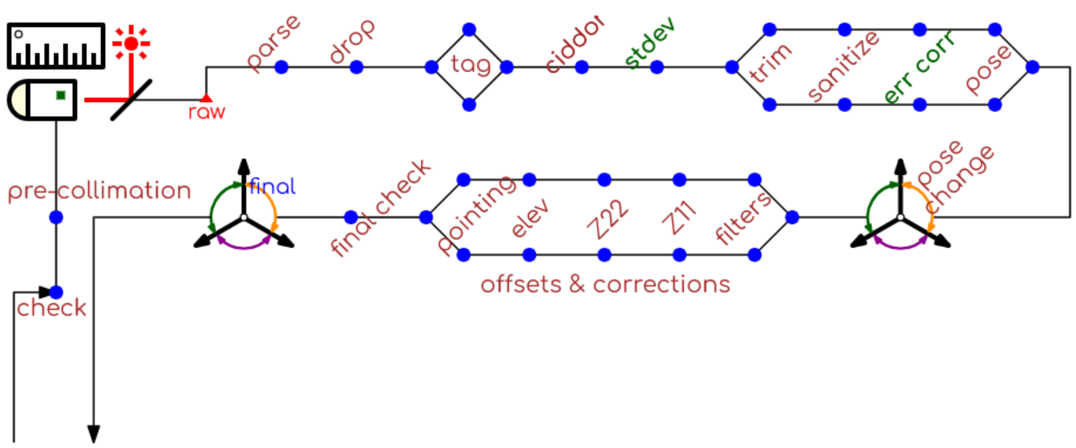

Figure 5-1The chain of steps involved in a single TMS pose correction. The sequence runs clockwise from bottom left.

Brief descriptions for the various terms in Fig. 5-1 follow:

- Check: It is a generic description of various checks to make sure it is okay/safe to proceed, including, for example, that the telescope is ready, and LBCs are authorized and other configurations are right, mirrors are in a safe state etc.

- Pre-collimation: sends a zero-movement position update to ensure that the mirror is on its collimation model.

- Raw: A "measure command" triggers a measurement and returns "raw" OPD data from each channel.

- Parse: Parses raw data into an internal structure for post processing.
- Drop: An option to manually select channels to drop exists, which has mostly been used for engineering.
- Tag: An internal step that tags the parsed raw data with some more information useful for later stages.
- Ciddor: The correction of channel OPD measurements to vacuum absolute lengths, using telescope temperature and humidity telemetry and the Ciddor equation (see also Refs. 3 and 4).
- Stdev: A newly introduced step calculates the standard deviation of three successive measurements on each channel and if the value is above some selected cut-off (currently 5 microns) the channel is dropped from the measurement.
- Error-check: A final check to decide which channel data can be used (i.e., data is reasonably good, this stage performs extra checks, such as that data must be within certain bounds of the reference distance, each retro reflector group must contain at least one channel, that an invertible matrix solution exists with available channels etc).
- Pose-change: Available vacuum-corrected channels, following the error check, are used to formulate and solve the linear approximation to the forward kinematics equations as in Equation (5). The output is a 6.d.o.f. vector returning the primary mirror to the same orientation and position as it was at the time the reference measurement was taken.
- Offsets and corrections: All commanded changes in M1 position since the reference pose was taken stored, and these known, commanded, pose changes are now "backed out" of the pose-change calculated in the preceding step. This step is necessary to prevent the TMS from undoing all of the deliberate pose changes arising from such things as z-correction associated with radially symmetrical mirror bending modes, optics pointing offsets and filter-focus-offsets.
- Final check: Telescope state check to ensure telescope is in ready state to receive active-optic correction.
- Corrections sent: The final corrections sent are the calculated pose change, corrected with offsets and corrections.

The evolution of the control software did not happen directly from modelling and "first-principles", but rather required a series of development steps informed from on-sky results during engineering time. The subtlety and complexity of the interactions of this type of metrology system with a mature telescope control system stem primarily from the fact that the real perturbations of pose in the telescope optics can be divided into two basic types: deliberate and unintentional. All of the deliberate changes in pose, arising from such things as pointing offsets, dithering, movements associated with Zernike correction, filter changes with associated z-offsets, must be allowed for and not "un-done" by the TMS pose correction. Adding to the complication is the importance of timing and telescope state. The system as it stands today is the result of a number of iterations, where specific issues have been identified, a solution determined, implemented and tested.

The goal has been to maintain "operability", without adding to the burdens of an already busy telescope operator and support astronomers. The system, once started, runs smoothly in the background; only requiring human intervention when the telescope is re-collimated and a new reference is required. If the system fails for any reason, care has been taken to ensure that it fails "smoothly". For example, the channel standard deviation test ensures that false corrections associated with spurious channel measurements are not sent. If the system stops working, the LBC operates exactly as it did prior to the implementation of the TMS, and image quality assessments guide telescope operators and support astronomers as to when a new active optics cycle is required whether the TMS is operating or not.

6. COMMISSIONING

By Q1 2022, iterative development of the control system described in the previous section had delivered a system that was robust and effective. The ability to maintain image quality over several hour periods and over large elevation changes (which previously would have required active optics correction) had been demonstrated. The basic system goals of operability, error handling, reliability and accuracy were met, and the decision was taken by observatory management to release the TMS for science operations.

During the course of developing and commissioning the TMS, an increasingly complex set of data was gathered. This was necessary to fully determine and characterize the complex interaction of TMS with the LBT TCS. An example of one of these plots and tracked data is given in Figure 6-1.

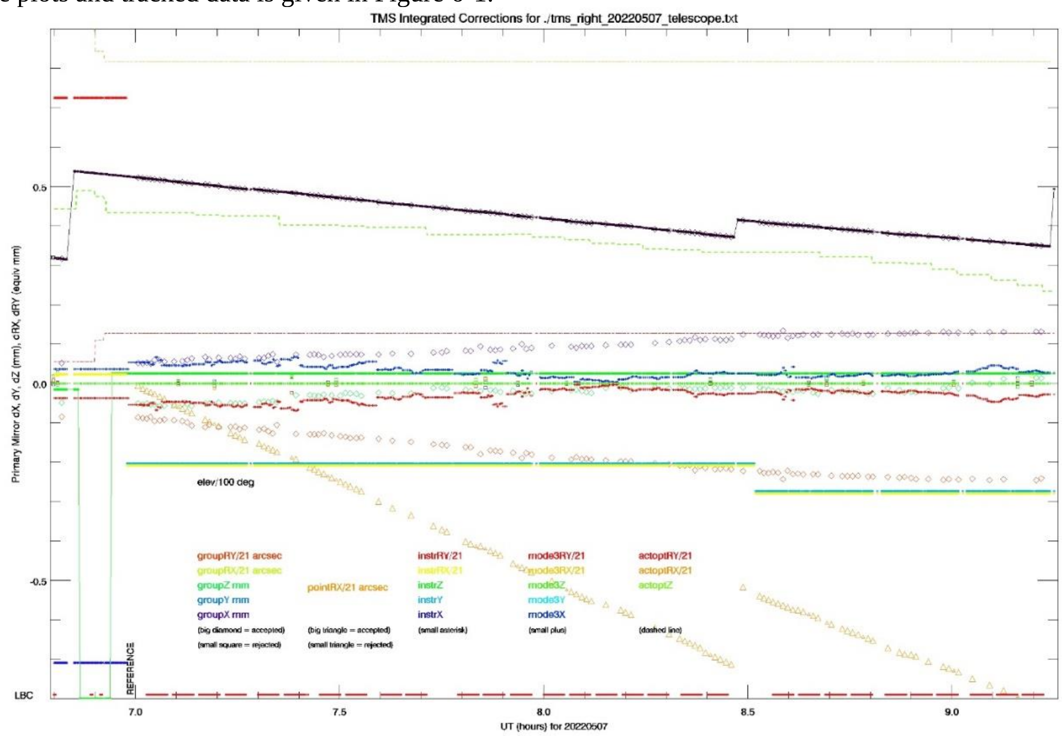

Figure 6-1 This "information-rich" plot was developed to track TMS performance and its interaction with other aspects of the TCS. Explaining the legend: the first column on the left indicates cumulative pose changes sent by the TMS, the second column indicates instrument offsets, such as filter-focus offsets, that TMS must allow, the third column refers to changes in M1 pose associated with commanded pointing, and the fourth column refers to commanded changes in M1 position associated with active optics. The black diagonal lines indicate elevation, with continuity indicating a single observed target. The sudden vertical changes in green "instrument offset Z" indicate that an FPIA run has occurred, and a TMS "reference" measurement was taken immediately afterwards. Subsequent to the reference measurement changes in pose are calculated with respect to this data set.

The interaction of the TMS with a mature TCS required careful attention to be paid to many details, and surprising interactions were common at the outset. By monitoring telemetry, corresponding image quality, and regular analysis of results, a number of details were worked out and overall system stability eventually confirmed.

A tool was developed to assess image quality in the science images as they become available, and to compare this image quality to the reported seeing from a DIMM monitor. When image quality degrades compared to seeing it is an indication that observing must pause and an image-analysis active optics run is required. This tool has proved to be useful not only as a gauge of the effectiveness of the TMS active collimation but also as a general aid to observers with the LBC. Figure 6-2 gives an example of the output of this image quality tool.

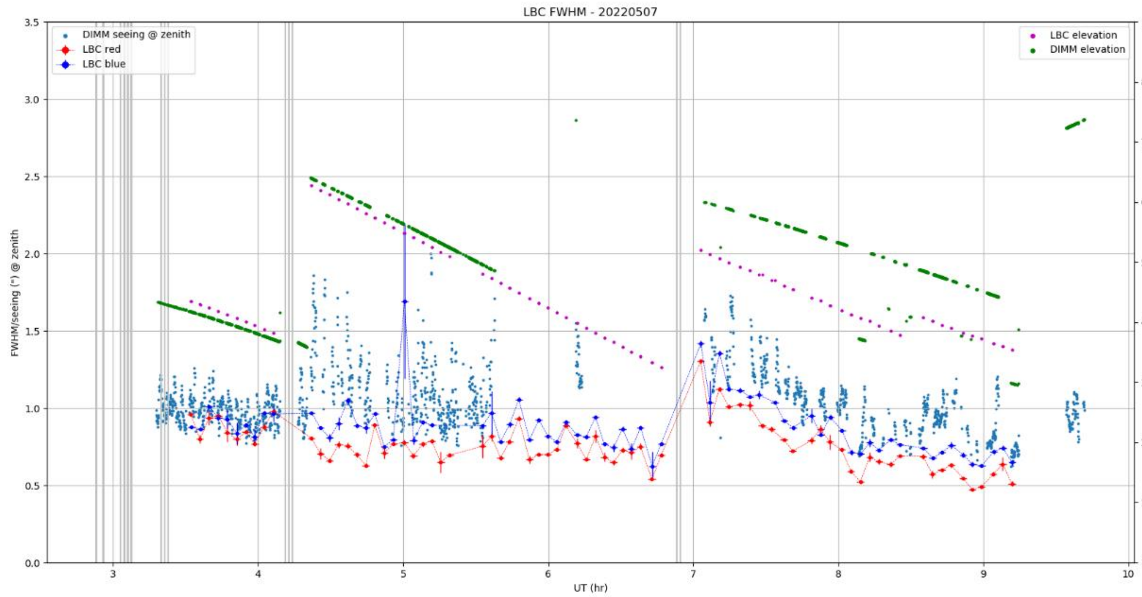

Figure 6-2 The image quality (IQ) of the LBC images is plotted for each image in blue and red dots according to the camera used (LBC Blue on the left eye and LBC Red on the right eye of the binocular telescope). Error bars in y give the rms in arcseconds of the image quality measurement, which is an average o the fwhm on the most central chip of the detector mosaic for each camera. The x error bar shows the duration of each exposure. The elevation of the telescope at the mid-point of each image is shown in magenta dots, tracing the change of target via jumps in their plot. The image quality does not depend only on how well the telescope is collimated, but also on the atmosphere. DIMM measurements are shown as gray-blue dots. Usually, the LBCs have a slightly better IQ than measured by the DIMM, thanks to their narrower wavelength coverage and some averaging of the turbulence. As atmospheric turbulence has a stronger effect at shorter wavelength, IQ is better for LBC Red than for LBC Blue. The FPIA runs mentioned in the 6.1 legend are shown here as vertical gray lines. Each of them corresponds to an extra-focal image taken with the LBCs. After the initial first 40 min spent on a target at a time when the telescope is stabilizing its temperature, collimation is done before going to the second target. For the following six hours, there is only one FPIA collimation done just before 7 UT when moving to a new target. It could likely have been skipped but observers still tend to be conservative. At around 8.5 UT, the telescope moved to a new target and the IQ continued to follow the seeing as well as it did before the move, showing that the TMS is doing its job!

TMS is routinely controlling relative positions of the primary mirror and correctors over distances of the order of 10 metres with the precision on a few microns. This control has been demonstrated to be maintained over periods of multiple hours. Over several months of science support, TMS has proven to be a robust and reliable tool. With more use of TMS in active mode, we will come to a point where observers are more confident in its capabilities. TMS will be the default observing mode at the LBT prime focus, thus saving every night a significant amount of time previously spent for multiple sequences of FPIA runs interlaced with observations.

7. THERMAL SHAPE CORRECTION

One limiting factor on the TMS performance is that it does not detect mirror shape. The borosilicate mirrors of the LBT are susceptible to shape deformation when the front and back plates have different mean temperatures and/or different temperature distributions. The production of good look-up tables for thermal shape correction of the borosilicate primary mirrors is particularly important for LBC observations, given the long intervals between active optics corrections with FPIA.

Various attempts have been made previously to produce look-up tables for thermal shape correction via the analysis of historical data, but this task has proved intractable, as the unstable thermal conditions perturb both the position of the optical elements and the M1 shape, and these at different rates. The TMS breaks this error-source-degeneracy. With the optics relative positions locked by TMS, there is now scope for producing accurate thermal models for mirror shape. The data presented below is extracted from measurements made on the night of March 29, 2021. Figure 7-1 shows a near linear decrease in glass temperature that occurred during this observing run. Thermal data is taken from 36 Front Plate and Back Plate Thermocouples. Measured Zernike focus (Z4) is fit to the difference in the mean temperatures of the front and the back plates of the mirror substrate.

In this instance, both the Blue and the Red channels of LBC were collimated by FPIA, then the achieved collimation state was maintained by the TMS for the Red channel side only, while a set of continuous images were taken of pupils suitable for post analysis by FPIA software. Figure 7-2 shows the measured Z4 aberration over the period for both Red and Blue cameras. The difference is striking. The Blue focus data shows a much greater departure than Red and at least 2nd degree functional dependence on temperature. The Red data is very close to linearly correlated with the glass temperature from Figure 7-1. Even the small "bump" in the mirror temperature data occurring at 07:00 UT, is replicated in the measured Z4.

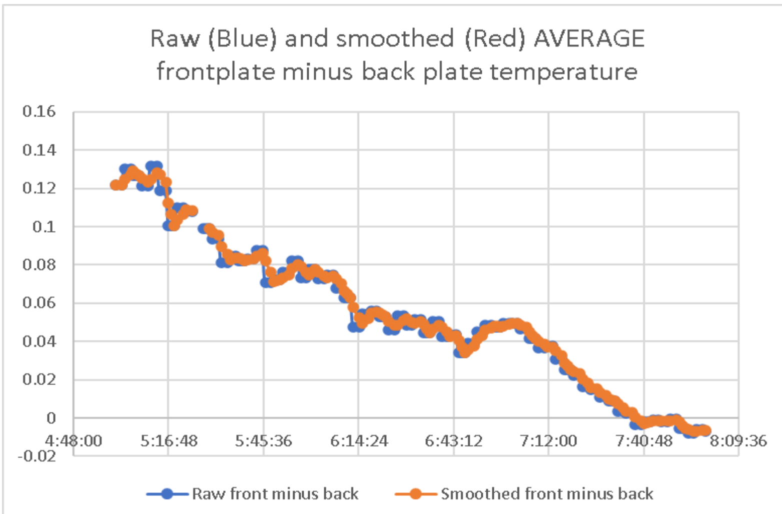

Figure 7-1 Average Front-plate minus Back-plate temperatures for the Red channel (blue was very similar).

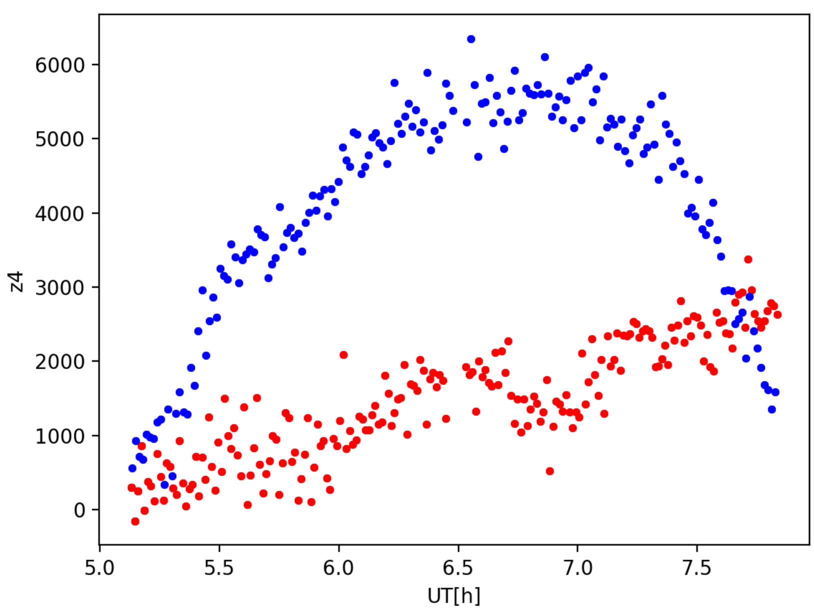

Figure 7-2 Z4 (required for correction) for Red and Blue cameras. Only Red was controlled by TMS. Blue focus combines contributions from structural deflection and mirror thermal; Red contains only mirror thermal shape contributions.

Other low-order Zernike terms showed correlation with temperature but with significantly weaker dependencies, as shown in Figure 7-3. Clear trends are visible but with lower magnitude than the Z4 dependence. However, in this case the temperature difference range in the M1 segment was only 0 K to 0.14 K, and in the future these terms will likely be controlled to improve performance when the mirror is less thermally stable.

The initial results for thermal shape correction using TMS position-corrected data are very encouraging. Now that TMS is being used routinely for science support large data sets are being produced that can be used to fit better models. It is expected that LBC performance will benefit still further once these are produced and implemented.

Table 7-1 below shows results from the linear thermal shape model for Z4 applied and run with TMS controlling mirror position on both Red and Blue channels.

Table 7-1 The thermal shape model for Z4 was tested while both Red and Blue channels were actively controlled for position with TMS. The "percentage model error" row gives the focus result given by the model (the "difference" row) divided by the convergence criterion for Z4 (250 nm). In the cases highlighted green the telescope was inside this convergence criterion, while ~half of these cases were outside of this convergence before the model correction was applied. In the yellow and four out of five of the red cases, the system was not converged but the model had corrected in the right direction, under-correcting. Therefore, in 19 out of 20 cases the thermal shape model improved telescope focus.

DX	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
FPIA result	-462	143	158	-381	-2900	-71	-286	-43	359	-393
Model Prediction	-433	225	370	-251	-1000	69	-62	66	241	-120
difference	29	82	212	130	1900	140	224	109	-118	273
percentage model error	11.60%	32.80%	84.80%	52.00%	760.00%	56.00%	89.60%	43.60%	-47.20%	109.20%
SX	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
FPIA result	328	16	916	-11	-3657	-1675	977	-5	717	-53
Model correction	-217	101	370	-71	-2032	-1041	1024	100	601	-7
difference	-545	85	546	-60	1625	634	47	105	-116	46
percentage model error	-218.00%	34.00%	218.40%	-24.00%	650.00%	253.60%	18.80%	42.00%	-46.40%	18.40%

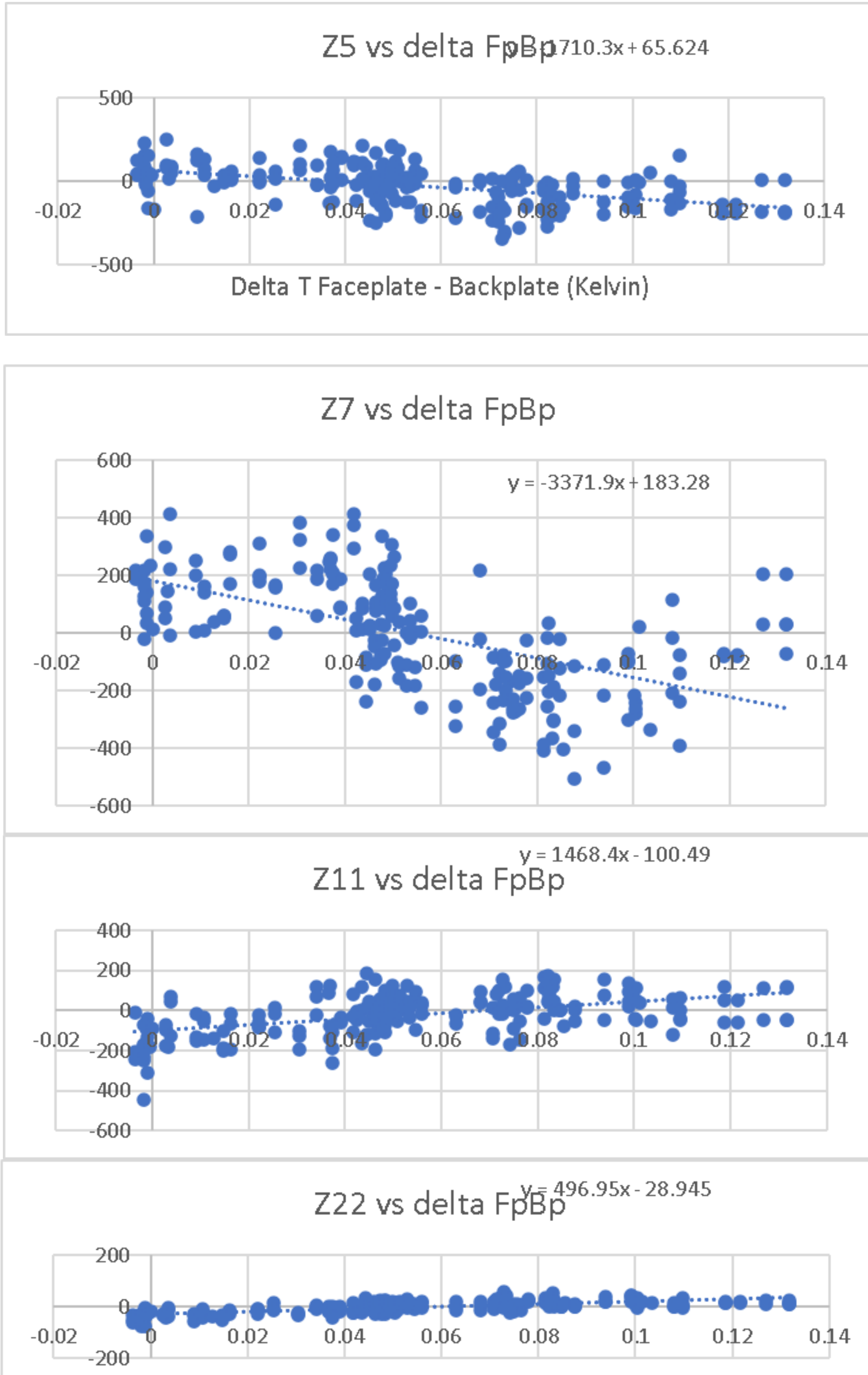

Figure 7-3 Clear trends are visible with thermal shape and low-order Zernike terms, though the magnitude is low.

8. CONCLUSIONS

A laser-truss based active optics system for the prime focus cameras has been commissioned on LBT. The system has proven to be operationally robust, accurate and simple to operate. Significant efficiency gains have been realized in LBC operations. The telescope can now maintain alignment for many hours without requiring recollimation. The TMS also allows the telescope to be collimated using fields at low airmass, then set to targets at high airmass with no aberrations introduced from optics position. The high stiffness of the LBT mirrors, compared to any other 10 m class telescope mirrors, make this possible without the introduction of significant gravitationally induced shape errors.

Thermal shape modelling with a TMS controlled telescope has already improved thermal focus considerably, and it is expected that higher resolution models incorporating other low-order modes can be produced and make further gains. It is expected that other telescope projects could realize benefits from this approach to telescope alignment.

9. ACKNOWLEDGEMENTS

Jim Fanson of GMTO and Christian Veillet of LBTO gave this system a “chance to be” back when it was just a proposal. John Hill has been the key figure in managing the very complex integration with the LBT TCS. The whole team have brought interest, enthusiasm and talent together to produce a “world first” direct-metrology active optics system.

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